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Intelligent Power Control of DC Microgrid

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***Abstract*— In this paper, an intelligent power management strategy is proposed for hybrid DC microgrid, including wind turbine, fuel cell and battery energy storage. The considered wind turbine has a permanent magnet synchronous generator (PMSG). In the considered structure, wind turbine operates as the main energy source while the fuel cell and battery bank are both auxiliary power sources. The main control objective is to supply the load power continuously while keeping all power sources in normal conditions. Hence, the fuel cell and battery bank are managed such that the system operates in normal condition and fuel cell will not generate excessive power. The proposed control scheme is based on the fuzzy algorithm. All simulations in variant operational modes are performed by MATLAB/Simulink and results show the effectiveness of the proposed control strategy.**

Keywords— Fuzzy Controller, PMSG Wind Turbine, Hybrid DC microgrid, Intelligent Power Management.

I. INTRODUCTION

The increasing rate for interconnection of distributed power resources and energy storages has created possibility of microgrid, both in AC and DC forms. Combining both AC and DC systems, hybrid microgrid has been proposed by many researchers [1]–[4]. Recently, with more applications of DC energy storages and DC renewable energy sources in industrial and residential parts, DC microgrid is getting more attentions. Some of advantages of DC microgrid are: 1) easier to build hybrid system with different sources and system can be scaled up gradually as needs increase; 2) higher efficiency because of elimination of power electronic conversion stages; 3) easier to integrate the renewable sources, especially for some DC sources such as PV, fuel cell, battery, super capacitor, and etc. [5]–[7]. Additionally, the dc system offers greater controllability, because it does not suffer from synchronization and reactive power compensation problems which are intrinsic to the ac grid [8]–[9]. Furthermore, the dc microgrid can be fully decoupled from the utility grid by an interface converter, enabling the seamless transition between the islanded operation and grid-connected modes. Because of the aforementioned factors, the dc microgrid is receiving increased attention recently, especially for small-scale commercial and residential applications. From point of view of power management strategies for microgrid, a series of research papers have been published for AC microgrid, leading to a standardized power management framework [10]–[12]. Using of intelligent control and power management is one of the crucial points for the microgrid operation. The target of such a system is coordinating the distributed microgrid terminals and smart loads, in order to mitigate the power intermittency and uncertainty, and provide a stable, reliable, and economic power supply for both local customers and the utility [13]. This paper is devoted to the proper operation of the hybrid DC microgrid by an intelligent management of power sources. In this configuration, wind turbine is the main demand supplier while fuel cell and battery bank are both auxiliary power sources. Due to the fact that most part of operation cost belongs to the fuel cost in the fuel cell, by controlling the amount of power generated by it, an optimal and low cost operation will be achieved. The purpose of current paper is to design an appropriate control scheme for the hybrid wind power, fuel cell and battery storage system in order to function in an optimal operational condition and tackle with the problems of the aforementioned researches. Next sections are organized as follows. In the section 2, structure of the hybrid energy system is presented. In section 3 the intelligent power management strategy is proposed. Section 4 consists of the controller design. Simulation results for four different operation modes are shown in section 5. Finally, section 6 includes conclusions.

II. HYBRID DC MICROGRID STRUCTURE

Fig. 1 exhibits the diagram of hybrid DC microgrid. According this Figure, the system contains a wind turbine, battery bank and a fuel cell. The wind turbine is as the main source in the system and the fuel cell with battery bank are auxiliary sources. There are four power electronic converters. A DC/DC converter coupled to fuel cell to regulate the DC voltage level, and a double side DC/DC converter coupled to the energy storage to transfer the battery power toward DC link and transfer the extra power from DC link toward the battery bank. Also there is an AC/DC converter that coupled to the wind turbine to convert turbine's power from AC to DC mode. At the end a DC/AC converter transfer the DC link power the load from DC mode to AC mode [14-17].

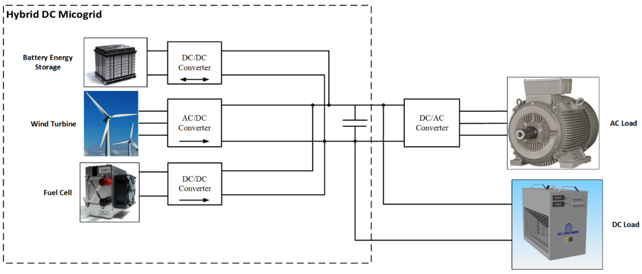

Fig. 1. DC Microgrid structure.

III. Intelligent Power Management Strategy

In order to design an effective control strategy is the most important part of research for the system under study. The control system always aims to achieve a more satisfactory and economic operation. In this section, an intelligent method to manage power generation and system optimal operation is proposed. In this structure, the main factors to control power sources are the power generated by wind turbine and the load demand. This means that, when the power generated by the wind turbine is more than the load demand, the excess energy must be stored in the battery bank unit. Besides, when the output power of wind turbine is not enough to meet the load demand, fuel cell and energy storage should be able to cover the shortage of power supply. It should be mentioned that repetitive quick start-up of the fuel cell makes its service life shorter. The fuel cell's start-up dynamic response has a large time constant to achieve a stable performance. Hence, to prevent reduction of fuel cell's service life and deal with the slow start-up dynamic response, which affects the balance supply and demand power, the fuel cell should always be kept in running state. This approach increases the hybrid system reliability and decrease the probability of loss of load when power of fuel cell is required [16]. To achieve aforementioned goals, whenever the wind turbine output power exceeds load demand, fuel cell is kept in a predefined low-level working condition and prevented from shut down. So, the excess power charges the batteries and when necessary, the stored energy in batteries will be utilized. Considering the output of the controller, which defines the reference signal for the fuel cell output power, and wind turbine power generation, the control of battery charge or discharge states becomes possible. The difference between generated and consumed power, ΔP, is calculated by adding the wind turbine and fuel cell powers, also subtracting the demand power (P_{Load}). Whenever, ΔP becomes positive, excess power should be absorbed by the battery storage unit which means battery charging. Similarly, if ΔP becomes negative, stored energy in batteries should be used to supply the load demand, in other word, batteries must be discharged. Equation (1) show the mentioned approach, where P_{WT} is the power produced by the wind turbine, PFC is the fuel cell output power, $P_{Battery}$ is the battery power and P_{Load} is the load demand.

$$
\begin{aligned}
P_{WT} + P_{FC} + P_{Battery} &= P_{gen} \\
\Delta P &= P_{gen} - P_{Load}
\end{aligned}
\tag{1}
$$

Finally, batteries, fuel cell and wind turbine output power shall cover the load demand completely. While designing the controller, it is important to consider proper rules, which prevent undesired interferences batteries and fuel cell performance. In this regard, fuel cell operation rules must be set to produce power just enough to assure optimal operation of hybrid system. Therefore, operation of the fuel cell and battery storage unit must be complementary. When the wind turbine output power exceeds load demand, the batteries should be charged and whenever they reach to a proper state of charge (SOC), the fuel cell power must be reduced in order to lessen fuel consumption. On the other hand, when the power generated by the wind turbine is not enough to supply the load and batteries are discharging, fuel cell must increase the output power to its maximum to prevent excessive battery discharge, besides, SOC should be taken into consideration. Frequent and excessive charge and discharge of the batteries shorten their service life. Considering above mentioned points will protect the batteries and will lead to cost effective operation. In this paper, fuzzy controller is proposed to control of optimal power management. Recently, fuzzy control has received increasing attention for simplicity of design. Fuzzy logic becomes superior to conventional control due to using incorporating expert knowledge in designing a controller [18]. Therefore, fuzzy control as a model-free approach is simply designed to control complicated systems. Also fuzzy control is used to improve the performance of systems. It is not only able to make decisions under specified conditions but also in the intervals between them. In this paper a Mamdani type Fuzzy controller is designed and fuzzy group types are Gaussian. For each input and output of hybrid system, appropriate rules are set and applied to the controller. Each input of the fuzzy inference system is divided to five intervals. Fig. 2 illustrates the division of membership function. Rules are established based on 5 levels of load demand which are tabulated in tables (1) to (5). The fuzzy controller has 125 membership functions. These rules are derived by considering the system operation in different modes and provide an optimal operation for each condition.

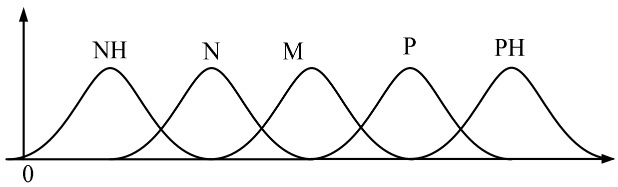

Fig. 2. An overview of proposed fuzzy membership functions.

TABLE I. Fuzzy Control rules for the first mode- very low level of demand power

P_{WIND} \ SOC	NL	L	M	H	PH
NL	PH	H	M	L	**NL**
L	NL	NL	NL	NL	**NL**
M	NL	NL	NL	NL	**NL**
H	NL	NL	NL	NL	**NL**
PH	NL	NL	NL	NL	**NL**

TABLE II. FUZZY CONTROL RULES FOR THE SECOND MODE-LOW LEVEL OF DEMAND POWER

SOC / PWIND	NL	L	M	H	PH
NL	H	M	L	NL	**NL**
L	NL	NL	NL	NL	**NL**
M	NL	NL	NL	NL	**NL**
H	NL	NL	NL	NL	**NL**
PH	NL	NL	NL	NL	**NL**

TABLE III. FUZZY CONTROL RULES FOR THE THIRD MODE- MODERATE LEVEL (M) OF DEMAND POWER

SOC / PWIND	NL	L	M	H	PH
NL	PH	PH	PH	PH	**H**
L	H	H	M	L	**NL**
M	NL	NL	NL	NL	**NL**
H	NL	NL	NL	NL	**NL**
PH	NL	NL	NL	NL	**NL**

TABLE IV. FUZZY CONTROL RULES FOR THE FORTH MODE- HIGH LEVEL (H) OF DEMAND POWER

SOC / PWIND	NL	L	M	H	PH
NL	PH	PH	PH	PH	**PH**
L	PH	PH	H	H	**H**
M	H	H	M	M	**L**
H	L	NL	NL	NL	**NL**
PH	NL	NL	NL	NL	**NL**

TABLE V. FUZZY CONTROL RULES FOR THE FIFTH MODE- VERY HIGH LEVEL OF DEMAND POWER

SOC / PWIND	NL	L	M	H	PH
NL	PH	PH	PH	PH	**PH**
L	PH	PH	PH	PH	**H**
M	PH	PH	PH	H	**H**
H	PH	H	M	L	**NL**
PH	M	L	NL	NL	**NL**

IV. SIMULATION RESULTS

In order to verify the mathematical model of hybrid DC Microgrid including of power electronic converter and the proposed power flow controller, the whole system has been simulated in MATLAB software environment. It is supposed that fuel cell is supplied 5KW of active power. Moreover, it is assumed that the output voltage of DC-DC converter should be regulated at 100V under different load current conditions and constant wind output power. For this purpose, load current changes as shown in Fig. 3. According to the presented results, it is achieved that the proposed control strategy is very suitable for fuel cell power generation system. In fact, by this control strategy the output voltage of fuel cell is regulated under different loading conditions and existing disturbances which may occur in fuel cell stack. For this purpose, a simulation of results based on the requested load power (Fig.3) is performed. In Fig. 4, the profile of wind turbine power has been shown. Moreover, in Fig.5, variations of fuel cell current and voltage are illustrated.

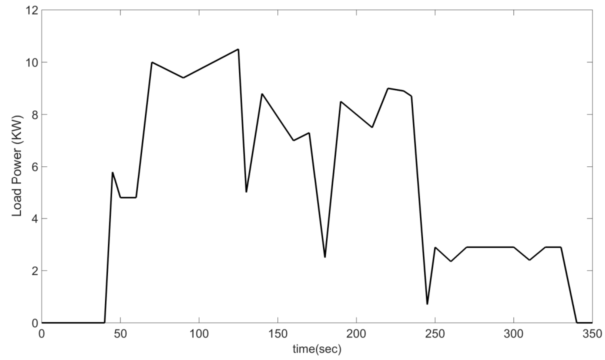

Fig.3. Load active power

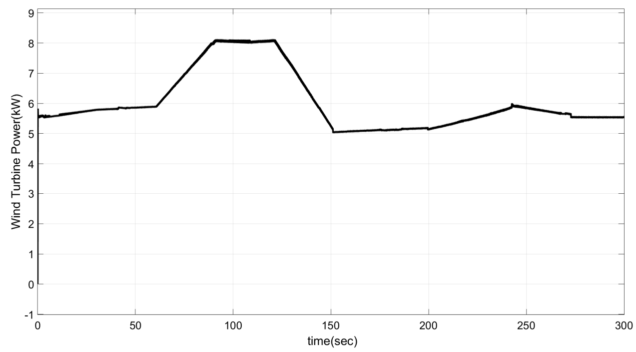

Fig.4. profile of wind turbine power

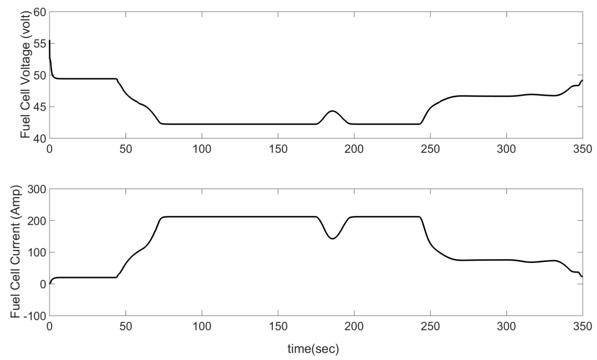

Fig. 5. Variations of fuel cell current and voltage in fuel cell

In Fig. 6 voltage and current variations of battery battery are shown. In this case, it is supposed the battery has been connected to DC microgrid and could absorb and deliver power. As illustrated, battery energy storage could deliver and absorb some power during different loading conditions.

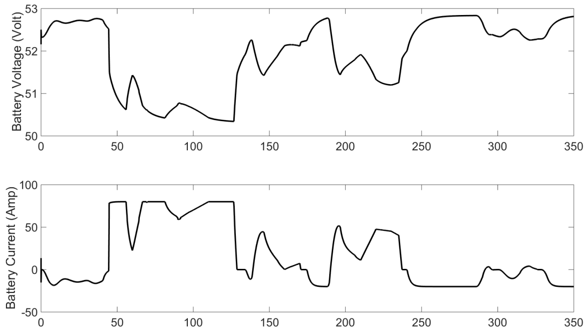

Fig. 6. Variations of battery current and voltage

In this condition, regulated voltage of DC-DC converter is presented in Fig. 7.

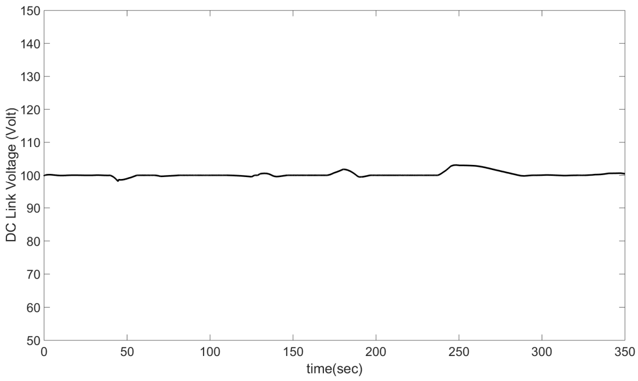

Fig.7. Output voltage of DC-DC converter

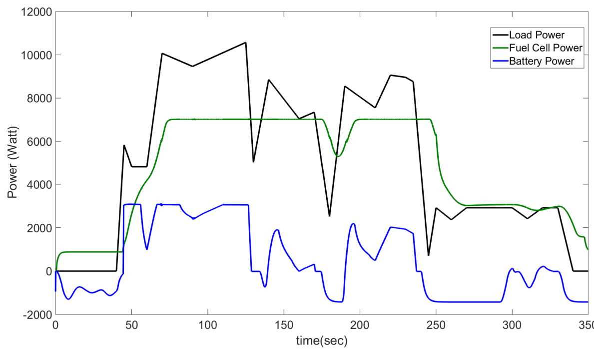

Fig.8. Output power for fuel cell, battery and load

In order to present that fuel cell and battery supply the load power, in Fig.8 output power of fuel cell and battery and load active power are illustrated. As shown, battery could deliver and absorb the power to keep the power balance in DC microgrid. Moreover, the battery's state of charge (SOC) is presented in Fig.9.

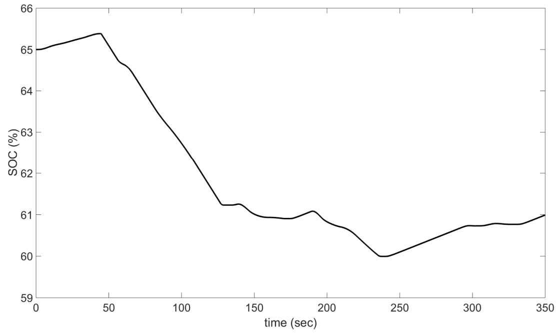

Fig.9. Battery's state of charge (SOC)

V. CONCLUSIONS

In this paper, power flow control of hybrid DC microgrid including wind turbine, fuel cell and battery storage is investigated. A fuzzy controller is designed for the proposed structure. The main goal of the control strategy is to provide an optimal operation for the system. The operation is such that power sources are interacted and cooperate to supply the load, entirely. Here, special attentions are given to the performance of the backup sources namely fuel cell and battery storage system. Considering the results driven by simulations of the system in different four operational modes, it demonstrates that there is no undesired interference between the performances of the backup sources. The other important goal of the proposed scheme is to supply the load appropriately and to establish a perfect balance between power production and consumption. Analyzing of simulation results show that the goals are satisfied and no loss of load occurred.

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